SEASONAL PATTERNS OF NITROGEN MINERALIZATION FOLLOWING HARVESTING IN THE WHITE SPRUCE FORESTS OF INTERIOR ALASKA

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Abstract: The effects of commercial timber harvesting upon nitrogen transformations were evaluated for the forest floor and mineral soils of mature white spruce *(Picea glauca)* forest sites in interior Alaska. Analyses of forest floor incubated *in situ* in mature forest and two recently harvested areas of different ages indicated an ammonium-dominated soil system for the unharvested area. Maximum NH_4-N mineralization rates (300 μg N / 100 g dry soil / day) were found in mid-summer and generally declined with the onset of fall. In the harvested areas, rates of NH_4-N accumulation were almost invariably lower than in the uncut area, a consequence of elevated levels of nitrification. Shortly after harvesting, NO_3-N concentrations were extremely high. Thereafter, they declined to levels slightly higher than in the mature forest. Nitrification was strongly enhanced by harvesting, and regular patterns within season were evident. For the youngest clearcut, the combined processes of ammonification and nitrification only occasionally supplied more nitrogen to the site on a daily basis than was supplied to the mature forest site. For the oldest clearcut, the supply from the combined mechanisms was variable and depended on time since clearcutting.

Until recently forest ecologists have considered one of the most important consequences of forest harvesting to be the removal of a large portion of the site nutrient capital in the harvested trees. Many past studies were concerned with the effects of clear-cutting upon soil nutrient reserves. For example, the effects of clear-cutting on chemical changes in forest floor organic matter (Covington 1981), woody litter decomposition (Abbott and Crossley 1982), soil microbiological properties (Smith *et al*. 1968; Theodorou and Bowen 1981) and soil solution chemistry (Hart *et al*. 1980) have been documented. With the advent of whole-tree logging, and consequently, the removal of branch material and potential needle litter, a substantial fraction of the nutrient pool formerly present on the site will be lost to subsequent generations of trees. Recent studies at the ecosystem level in a variety of forest site types have evaluated nutrient losses and changes in site productivity resulting from whole-tree harvesting (Adams and Boyle 1982; Mann and West 1981; Silkworth and Grigal 1982, and many others). With any type of logging, replacement of these losses will largely arise from the remaining stock of nutrients. Under whole-tree harvesting, it is likely that this reserve will be taxed severely. The rate at which nutrients, especially mineral nitrogen, are supplied from this reserve will undoubtedly have a substantial effect, in conjunction with other stand parameters, upon not only the re-establishment of the stand but also upon the growth rate of young trees.

The biochemical aspects of nitrogen mineralization and nitrification have been well understood for some time (Robertson 1982). Increased importance has been placed upon

119

nitrogen mineralization as a major factor in the maintenance of site productivity as indicated by a number of recent studies evaluating the effects of certain forest management practices upon nitrogen mineralization and nitrification. Urea fertilization of forest soils has been found to stimulate net nitrogen mineralization (Johnson *et al.* 1980) and nitrification (Popovic 1977). Similarly, mineral nitrogen production was increased by afforestation (Williams and Cooper 1979) and by ploughing cultivation (Powlson 1980). The latter could readily be likened to forest site scarification. In Greece, Nakos (1980) reported that only one herbicide (asulam) considerably reduced soil nitrification. Unfortunately, while the importance of soil nitrogen mineralization and nitrification to forest production processes has been recognized (Likens *et al.* 1969), few studies have dealt with the effects of commercial timber harvesting upon nitrogen mineralization. Glavac and Koenies (1978a,b) in Europe, indicated that clear-felling increased net nitrogen mineralization by a factor of three. In North America, net nitrogen mineralization is almost always increased by clear-felling (Matson and Vitousek 1981) but this is strongly dependent upon the physical and biochemical conditions of the soil. Cold, dry, or anaerobic soils may prevent substantial nitrification even in the presence of substantial ammonium substrate (Vitousek 1981).

Soil temperature and moisture content are the important factors controlling the mineralization of nitrogen. It follows that, in cold-dominated soils such as those found in portions of interior Alaska, the processes of organic matter decomposition and nitrogen mineralization occur at slower rates than in warmer, temperate-latitude soils. The underlying question to be asked is this: if physical variables controlling nitrogen mineralization are adversely affected by the removal of forest cover, what can the mineralization and nitrification rates be expected to do? Rapid short-term increases in the rate due to increased surface temperature and available moisture may be offset by excessive leaching. Over a longer period of time, the mineralization rate may decline as the forest floor dries up. Competition for mineral nitrogen reserves by weed species may further limit the nitrogen available for uptake by desired species such as white spruce. As well, upon decomposition, the remaining mass of primary root tissues with its typically high C/N ratio will likely become a carbon source for microbial activity. Thus, soil nitrogen reserves may become temporarily unavailable while supplying these microbial demands.

Increasing development of Alaska's interior forests for a variety of wood products dictates the need for an understanding of changes in productivity of the land base with use and time. Nutrient cycling studies in interior Alaska have, to date, documented many of the important nutrient pool sizes and fluxes for the predominant covertypes but there is a lack of information on the effects of forest management activities upon these nutrient reserves and processes.

There are four principal objectives in our present program. They are:

- to quantitatively assess and model the effect of timber harvesting disturbance upon the seasonal breakdown and transfer of organically-bound nitrogen to available form within the forest floor and mineral soil of mature white spruce stands;

- to determine, using these mineralization rates and other estimates of N-pool sizes for system components, the short-term and potential long-term effects of fluctuations in these rates due to disturbance upon the site and system nitrogen balance;

120

- to provide a predictive mechanism for the potential replenishment and/or depletion of nitrogen supplies with disturbance; and

- to elucidate and test, in conjunction with the above, methodology associated with the use of polyethylene bags in field incubation experiments, through a variety of laboratory and field experiments.

The present paper presents an overview of aspects of nitrogen mineralization in the forest floor, within the context of the first objective.

Materials and Methods

Study Area

The study site is located in the Bonanza Creek Experimental Forest, 32.2 km west of Fairbanks, Alaska (64°45' N, 148°15' W). Three sites were selected for study. The control area is a mature, 110-year old stand of white spruce, with a minor component of white birch *(Betula papyrifera)* and alder *(Alnus crispa)*. The moss layer in this stand is continuous, consisting principally of the feathermosses *Pleurozium schreberi*, and *Hylocomium splendens*. A harvested area resulting from commercial logging in 1977 is located immediately adjacent to the control on the east; a 1978 cut lies immediately to the west. Clear-cuts were chosen in order that a sequence of 'months after clear-cutting' could be portrayed. For the most part, the integrity of the forest floor has been destroyed within the clear-cut areas, resulting in a layer of mixed organic material, logging slash and fine roots and twigs to a maximum depth of approximately 15 cm. Pioneer ground vegetation within these areas is comprised principally of *Mertensia paniculata*, *Rosa acicularis*, *Epilobium angustifolium*, *Galium boreale*, *Equisetum arvense*, and *Calamagrostis canadensis*.

This area of Alaska was unglaciated; the mineral soil underlying all three sites is a micaceous loess silt (Péwé 1955) over precambrian schist and gneiss bedrock (Johnson and Hartman 1971). The study sites are in the zone of discontinuous permafrost at about 200 m elevation, with gently-sloping southern aspects. Some climatic data for the Bonanza Creek Experimental Forest are given by Barney and Berglund (1973). Generally, the climate of the region is continental, with a growing season limited to about 100 days by late-spring and early-fall frosts. Mean annual air temperature is $-3.5°C$ and average annual precipitation is 28 cm, the bulk of which falls as rain.

Field Methods

In situ field incubations using buried polyethylene bags (Eno 1960) were used to estimate nitrogen mineralization. This method prevents leaching and plant uptake of mineral nitrogen (NH_4-N and NO_3-N) while at the same time maintaining aerobic conditions and preventing undesirable moisture loss.

Within each of the disturbed sites a preliminary vegetation survey by line-point revealed the basic ground cover pattern. This allowed for the stratification of sample points within the vegetatively heterogeneous clear-cut areas. Thirty permanent sample points were established randomly within each site. Sampling was on a monthly basis for August and September, 1979 and from June to September, 1980. In addition, the overwinter periods 1979 to 1980, and 1980 to 1981 were also monitored. At the start of each sampling period

a standard soil core (15 cm diameter) was removed from the vicinity of each sampling point. The mineral soil and forest floor were separated and each was thoroughly mixed. Major roots and woody debris were removed. A subsample of each was taken for initial mineral nitrogen (NH_4^+, NO_3^-) content. The remaining mixed material was molded into a thin, 1 cm disk, enclosed in a 0.8 mil polyethylene bag (Presto Products, Appleton, WI) and re-inserted into the core hole at the appropriate depth (8-10 cm for forest floor; 20-22 cm for mineral soils). The core-holes were re-covered and the samples left to incubate under a natural temperature regime for the period of interest. Subsamples were removed to the lab and frozen at $-10°C$, pending analysis for NH_4-N and NO_3-N. At the end of the incubation period, the field samples were removed, transported to the lab, and kept frozen until analyzed.

Laboratory Methods

Ten grams of all samples were thawed and immediately extracted for NH_4-N and $NO_3 + NO_2$-N using 2 N KCl (Bremner 1965), in a 7.5:1 ratio (soil:KCl). Duplicate extracts were shaken for 1 hour, suction-filtered and analyzed colorimetrically using a modified dual channel Technicon II Autoanalyzer system with a sensitivity of 0.01 ppm. NH_4-N was measured on 1 channel by a variation of the Technicon industrial method No. 98-70W. On the second channel, the extracts were passed over a copperized cadmium column, reducing the nitrate to nitrite. Total nitrite was analyzed using a variation of the Griess reaction and Technicon industrial method No. 100-70W. Results are expressed on an oven-dry weight concentration basis. Moisture content was estimated by oven-drying subsamples at 65°C (forest floor) and 100°C (mineral) for 48 hours.

Results and Discussion

Results of available nitrogen analysis for the organic horizon (sub- and incubated samples) are shown in Figure 1. The blocks of bars on the far left illustrate NH_4-N and NO_3-N levels from mid 1979 through May, 1981, 22 continuous months of incubation, for the control area of 110-year old white spruce. Similarly, the blocks in the center and on the right express the same factors over the same period for clear-cuts resulting from harvesting in 1977 and 1978.

In the uncut situation, the concept of an ammonium-dominated climax ecosystem as reported by Rice and Pancholy (1972) can be seen. In such systems, ammonium is probably the preferred nitrogen species by plants since less energy must be expended to incorporate nitrogen in NH_4 as opposed to nitrogen in NO_3, into proteinic structures (Haynes and Goh 1978). Little or no nitrification and associated nitrate are present. Unincubated ammonium levels (instantaneous net pool size) in the soil varied from approximately 5,100 μg N / 100 g dry soil to over 11,000 μg N / 100 g dry soil, indicating a wide variation in background ammonium levels seasonally. Despite this, seasonal patterns of nitrogen mineralization were detectable and are listed in Table 1. August of each year shows the highest values, with subsequent decreases in fall and overwinter. This is likely in response to favorable post-summer microclimatic and site conditions. Earlier in the season the soil temperature regime may have favored large amounts of heterotrophic decomposition, resulting in the creation of organic residue with wide C/N ratios. Available nitrogen may have been at a premium while supplying these microbial demands.

In the disturbed areas, background levels of NH_4-N do not differ drastically from the

122

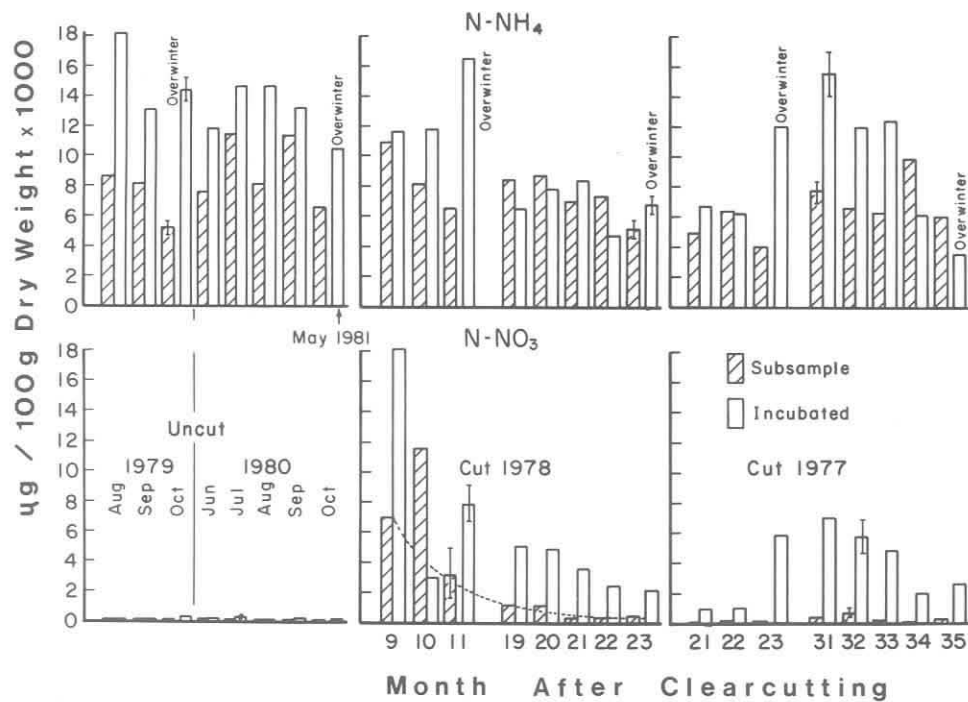Figure 1. Distribution of available nitrogen (N-NH$_4$ upper; N-NO$_3$ lower) by month in the forest floor of cut and uncut stands of 110-year old white spruce. Each bar represents 30 field points plus 2 lab reps. Some typical standard error bars are shown. Incubation period was approximately 30 days in all cases, except where overwinter *in situ* incubations are indicated.

Table 1. Seasonal values of soil nitrogen mineralization (ammonification) in the forest floor of a 110-year-old stand of white spruce[a]

Period	Mineralization (ammonification) rate (μg N/100 g dry weight/day)
August 1979	311.40
September 1979	166.40
Overwinter 1979-1980	37.97
June 1980	154.22
July 1980	86.51
August 1980	223.01
September 1980	60.44
Overwinter 1980-1981	16.93

[a]The values reported here and in subsequent tables have as of yet not been corrected by weight-volume estimates for expression on an area basis. Each value is based on differences between averages from sets of 30 points.

123

Table 2. Seasonal values of soil nitrogen mineralization in the forest floor following harvesting in 110-year-old white spruce

Time after harvesting (months)	Mineralization (ammonification) rate (μg N/100 g dry weight/day)	Mineralization rate from uncut area (μg N/100 g dry weight/day)
9	21.19	311.40
10	128.44	166.40
11-18	42.40	37.97
19	net loss	154.22
20	net loss	86.51
21	50.87[a]-55.77[b](53.32)[c]	223.01-311.40[d]
22	net loss	60.44-166.40
23-30	7.16[a]-33.51[b](20.34)[c]	16.93- 37.97
31	281.10	154.22
32	149.37	86.51
33	214.45	223.01
34	net loss	60.44
35-42	net loss	16.93

[a]Area harvested in 1978.

[b]Area harvested in 1977.

[c]Average.

[d]Where two values appear in this column, compare the first to the ''a'' value in the previous column, and the second to the ''b'' value.

uncut area, although variation in levels from the clearcut areas is reduced. However, net rates of NH_4-N accumulation, as indicated by accumulation of NH_4-N above background levels were lower than rates of accumulation for the uncut area with the exception of two mid-summer periods nearly three years after harvesting (Table 2). In many cases, a net loss of NH_4-N can be noted in the cleared areas. Several years of decomposition may be initially required before NH_4-N is finally released to the site. However, since harvesting might be generally expected to enhance conditions of temperature and moisture favorable to mineralization, it is more likely that nitrification has been stimulated by favorable conditions, one of which might be a readily-available source of NH_4-N. This is verified by the data for the distribution of NO_3-N (Figure 1). Net NH_4-mineralization rates, averaged over all sampling periods by cut and uncut area, are approximately twice as large for the control situation. This is in part due to the number of net losses recorded for the harvested sites. It is important to note that the gross mineralization (ammonification) rate in the harvested areas is at least equivalent to that of the uncut situation. Net NH_4-mineralization is less in the cleared areas due to bacterial oxidation of NH_4-N into NO_3-N.

Nitrate is much more prevalent in the disturbed areas and it is possible that it is preferentially taken up by many of the plant species growing there. Plants with a large photosynthetic capacity, such as those found in disturbed situations, might be expected to have a net energy balance which would allow the expenditure of energy necessary to push the oxidation state of nitrogen from +5 to −3, as it occurs in ammonium, and many proteinic associations. Middleton and Smith (1979), working with grasses, indicate that the difference in total energy costs for nitrogen uptake is only eight per cent greater when the nitrate form is assimilated in favor of the ammoniacal form. The excess NO_3-N found

124

in the harvested areas is likely rapidly leached from the site, but may also be assimilated as *Calamagrostis* becomes established on the site. On the other hand, early successional plants may follow a strategy of preferentially utilizing reduced nitrogen (NH_4) in favor of NO_3-N, thus saving energy which could be used for carbon fixation and growth. The form in which nitrogen is taken up is important when considering the ability of white spruce seedlings, for example, to compete effectively for nitrogen with other species.

Nine to 11 months after harvesting, NO_3-N levels are extremely high and varied. Thereafter, they decline to relatively low levels, although remaining higher than in the mature forest. The hypothetical decline of background levels of NO_3-N is indicated by the dotted line in Figure 1. In all cases except for one, nitrification substantially increased NO_3-N levels in incubated bags. After the 19th month following harvesting the levels of NO_3-N from incubated samples were always higher than sub-samples taken from the site (for the next incubation period) immediately following removal. This indicates that NO_3-N is being rapidly leached from this system or taken up by plants. (NO_3-N is excluded from root uptake and is unable to leach from the samples incubated in polyethylene bags and is essentially "captured" for analysis.) Rates of nitrification are given in Table 3. If these values are plotted against 'months after harvesting', as in Figure 2, seasonal patterns of nitrification can be readily seen. High rates of nitrification appear to cluster around mid-summer with subsequent decreases as the year progresses. Between nine and 40 months after clear-cutting, the maximum rate of nitrification does not appear to be related to time after harvesting, but rather to seasonal (climatic) phenomena. These patterns of fluctuating rates should be superimposed upon a general decline in absolute levels of soil NO_3-N (Figure 1) as nitrate produced is lost from the forest floor.

When the mineralization rate for total available nitrogen is calculated (Table 4) for the harvested areas, and compared to ammonification (the principal source of available nitrogen) rates from the uncut areas, some interesting patterns of nitrogen supply emerge. These are plotted in Figure 3. For the youngest clear-cut (cut 1978) the combined processes of ammonification and nitrification only occasionally supply more nitrogen to the site on a daily basis than is supplied to the mature forest site in the uncut situation. In fact, the patterns of supply from two essentially different strategies are very similar on a seasonal basis. This is an indication of the shift in microbial processes that might occur in a disturbed ecosystem. However, since NO_3-N may be rapidly leached from the system, the net amount of nitrogen made available consists to a large extent of ammonium. Thus, a net decline in total available nitrogen supplied to the site may occur in the cleared areas. For the older clear-cut (cut 1977), the rate of nitrogen supply to the site is much less than the uncut area for the latter part of the 1979 growing season, but much greater for most of the 1980 growing season. The depression/resurgence of the supply mechanisms for this site, as contrasted between 1979 and 1980, reflect seasonal fluctuations of both nitrification and ammonification. The patterns suggest that shortly after harvesting, soil nitrogen mineralization processes are governed more by substrate chemistry than by environmental influences. In 1979, the youngest (1978) clear-cut (see Figure 3) receives nitrogen at almost exactly the same rate as the harvested area. A year later, in 1980, when it is two years old, small deviations in the supply rate can be noted. In contrast the older (1977) clear-cut, shows moderate deviations two years after cutting (1979), but larger deviations from the uncut supply rate in 1980, 3 years after harvesting. After 30 months ammonification once again provides net gains as nitrification declines, and nitrogen may be supplied to the site at a rate greater than would occur in the uncut situation. This is exemplified for the rate of supply in 1980 for the older cut (cut 1977); the pattern of supply is very similar, but the rate, at least for the summer months, is at least twice that of

Table 3. Seasonal values of soil nitrification in the forest floor following harvesting in 110-year-old white spruce

Time after harvesting (months)	Month of year	Nitrification rate (μg N/100 g dry weight/day)
9	August	369.98
10	September	net loss
11-18	Over-winter	19.79
19	June	123.32
20	July	103.45
21	August	32.62[b]-92.66[a](62.64)[c]
22	September	30.17[b]-36.96[a](33.57)[c]
23-30	Over-winter	9.79[a]-24.06[b](16.93)[c]
31	June	233.53
32	July	142.49
33	August	168.48
34	September	30.03
35-42	Over-winter	10.51

[a]Area harvested in 1978.
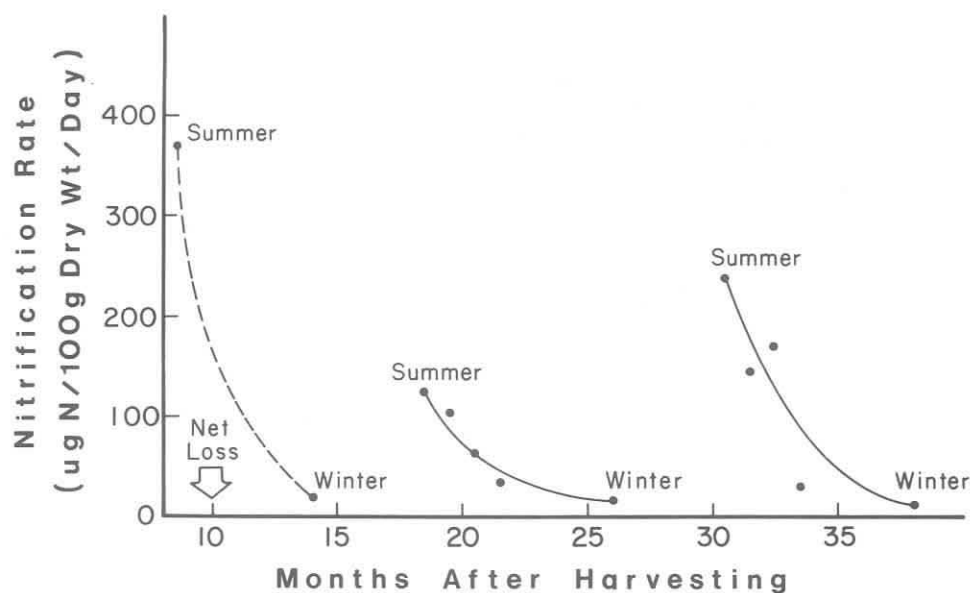[b]Area harvested in 1977.
[c]Average.

Figure 2. Seasonal patterns of soil nitrification. Lines represent best fit by eye. The dashed line reflects a hypothetical decrease in the rate of nitrification, given an unexplained net loss in month 10 (see Table 3). Based on differences between averages from sets of 30 points.

Table 4. Seasonal values of total soil nitrogen mineralization (ammonification + nitrification) in the forest floor after harvesting in a 110-year-old white spruce stand

Time after harvesting (months)	Corresponding month of year	Ammonification + nitrification rate (μg N / 100 g dry weight / day)
9	August	391.97
10	September	128.44
11-18	Over-winter	62.19
19	June	123.32
20	July	103.45
21	August	88.39[b]-143.53[a](115.96)[c]
22	September	30.17[b]- 36.96[a] (33.57)[c]
23-30	Over-winter	16.95[a]- 57.57[b] (37.26)[c]
31	June	514.63
32	July	291.86
33	August	382.93
34	September	30.03
35-42	Over-winter	10.51

[a]Area harvested in 1978.
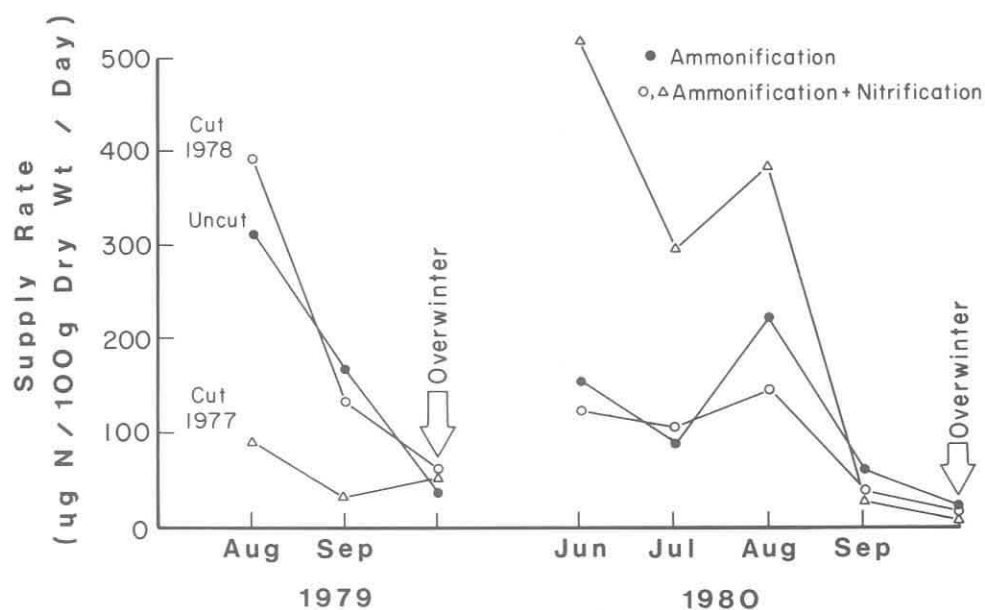[b]Area harvested in 1977.
[c]Average.

Figure 3. Comparison of soil nitrogen supply mechanisms for harvested and unharvested areas of 110-year-old white spruce.

127

Table 5. Net gains and variation in NH_4-N concentrations from cut and uncut stands of 110-year-old white spruce. Based on a composite sample of data sets from all sampling periods

	Clearcuts		Control
	Youngest	Oldest	110 year-old White Spruce
% of bags showing positive gains in NH_4	58	68	88
Average $(S/\overline{X})$ for subsamples	0.86	0.51	0.58
Average $(S/\overline{X})$ for incubated samples	0.92	0.50	0.52

the uncut area or the youngest clear-cut. Soil processes may be under strong climatic control at this point in time after harvesting, although decomposition of roots and other organic debris left on the site, will certainly have commenced, and variations in the C/N ratio of newly-deposited litter from pioneer plants may also be asserting an effect.

Table 5 shows net gains and variation in NH_4-N values from all three areas. Almost 90 per cent of the bags in the control area of mature spruce showed positive gains in NH_4-N concentration. Conversely, not quite 60 per cent of the bags incubating in the youngest clear-cut showed positive gains. The oldest clear-cut was intermediate. Variability in data, as illustrated by the coefficient of variation, is increased upon harvesting, but with time, may be reduced to its original level or below.

Matson and Vitousek (1981) also evaluated clearcutting effects upon nitrogen mineralization processes. They found similar increases in nitrification which they attributed in part to the initial population size of nitrifying bacteria. They also indicated that mineralization (total NH_4-N and NO_3-N) was increased in one clear-cut over the control after a period of only $1^1/_2$ years. We have reported on a similar pattern, about 3 years after harvesting (Figure 3). We have also shown that net ammonification by itself was increased in one of the cleared areas, for this same point in time (Table 2).

It becomes very hard to predict what the nature of nitrogen supply from the site's soil resource to a growing forest might be 100 years from now, given the wide range of management options available and their effects on soil properties. For example, C/N ratio, a strong control of microbial and chemical activity, can be changed drastically simply by time and type of harvesting and post-harvesting site treatment such as chipping of slash. The nature of the competing vegetation will also be important. In the long-term, seeding, planting, mulching, herbicides, thinning, fertilization, no-treatment, etc., will all have differing effects upon soil nutrient supply. Ultimately, as with most aspects of forestry, the final question to be asked is: can the management strategy be continually repeated successfully on the variety of site qualities encountered in a given region every 100 years? As well, is it possible to have rotations, within which nitrogen availability is not an important limiting factor to growth, and where successful forestry could be realized, in a shorter period of time?

Certainly, management decisions based on previous knowledge of the impact of site preparation, seedfall, seedling recruitment, stand growth and soil fertility are invaluable. As far as the latter is concerned, for example, it would be desirable to know what the mineralization rates are of nitrogen in the soil immediately after harvesting. It is also important to know, for the most common management regimes, what levels of soil nitrogen supply might be expected at the end of rotation, just prior to the second cut, based on the uptake rate of the currently growing forest, and the mineralization rate of soil N in an aging ecosystem. We do know that within certain temperate coniferous forest ecosystems it may take 20 to 30 years to replace, through de-novo inputs to the system, the total nitrogen lost from the site under conventional logging (Gordon 1979). Under whole-tree logging, or in climatically-cool regions such as Alaska, this period may be much longer. Information on the rate of nitrogen mineralization in relation to other element recycling is also becoming available. Sulphur, for example, is mineralized at a much faster rate (Tabatabai and Al-Khafaji 1980). From the management point of view, the rate of supply of nitrogen and other nutrients to seedlings of a desirable species and the survival of these seedlings is of utmost importance. Thus N-mineralization should be evaluated as a strong component of a nutrient replenishment/depletion model, where the nitrogen available for seedling uptake reflects the net amount available after supplying competing vegetation and losses to other unavailable pools and pathways.

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